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ORIGINAL ARTICLE

Effects of slope position and land use on the stability of aggregate-associated organic carbon in calcareous soils

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Abstract Topography and land use affect soil organic carbon (SOC) storage, stabilization, and turnover, through several biogeochemical processes. This study investigated the aggregate composition and SOC content of bulk soils and aggregates at different slope positions under different land uses in a typical karst catchment of southwestern China. Our results show that the proportion of macro-aggregates and the SOC content of bulk soils and aggregates at different slope positions decreased from the upper to the lower slope. The SOC content generally increased with an increase in the mean weight diameter and proportion of macro-aggregates under different land uses. Our results indicate that macro-aggregates in forest and grassland soils make a greater contribution to both aggregate composition and SOC content than that in arable land soils. Therefore, converting farmland to forest or grassland can facilitate the accumulation of macro-aggregates as well as the storage of SOC.

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1 Introduction

The atmospheric carbon dioxide (CO_2) concentration has significantly increased since the Industrial Revolution, mainly due to fossil fuel combustion and land use change (Canadell et al. 2007). The carbon (C) stock in soils is 3500–4800 petragrams (Pg; 10^{15} g), and soils are responsible for half of atmospheric C recycling (Lehmann and Kleber 2015). It is important to identify the factors controlling soil organic carbon (SOC) storage and stabilization to understand how SOC affects soil structure and function, atmospheric composition, and climate change (Feng et al. 2010). Stable aggregates improve the stability of soil structure and enable the protection of SOC through many biological and physicochemical processes (Bast et al. 2015). Aggregate-associated SOC, with a different turnover rate, is an important factor when evaluating the C cycle.

The process of regional rock desertification is an ecological crisis that leads to the impoverishment of local residents in karst regions of southwestern China (Yuan 1997). The storage and stabilization of SOC are important for ecosystems in karst regions to ensure that land production capacity is maintained and land degradation is prevented. SOC distribution of soil profiles under different land uses, soil types, and vegetation types in karst regions has been investigated (Han et al. 2015, 2017; Zhu and Liu 2006). However, little research has been reported regarding the effects of slope position on SOC stabilization in this area. In this study, we investigated aggregate composition and SOC content in bulk soils and aggregates at different slope positions under different land uses. The aim of this study was to clarify how land use and slope position affect aggregate C sequestration. The results will be useful in developing policy to improve agricultural production and protect the fragile soil in the karst regions of southwestern China.

2 Materials and methods

2.1 Site description, sampling, and experimental design

The study area is in Chenqi village (26°15′N, 105°46′E), Puding county, southwestern China, with an average altitude of 1350 m. The region is controlled by a subtropical, monsoonal and humid climate with an average annual temperature of 15.1 °C and a mean annual precipitation of 1315 mm (Zhao et al. 2010). The soil in this region is calcareous, with a silty loam texture. The land use types of the region mainly include secondary forest, bush, abandoned orchard, grassland, arable land, and abandoned farmland (Fig. 1), which are also widespread in other karst calcareous soil areas. Soil samples were collected from the upper, middle, and lower slopes (including foothills) of three adjacent mountains in a typical karst catchment in June 2016 (Fig. 1). A description of the soil properties is given in Table 1.

Soil samples were collected from surface soil (0–10, 10–20, and 20–30 cm depth), and air-dried at room temperature. Part of the dried soil was ground to pass through a 2.5-mm sieve as bulk soil, while another part was stored without grinding for the separation of soil aggregates. Soil samples were separated into: (1) macro-aggregate (250–2000 μm), (2) micro-aggregate (53–250 μm), and (3) silt and clay fraction (<53 μm) by wet sieving (Six et al. 1998). The separated aggregates from wet sieving were dried at 55 °C until a constant weight was achieved. Dried samples of bulk soils and aggregates were ground to pass through a 149-μm sieve. Powder samples were treated with 0.5 mol·L^{-1} HCl for 24 h to remove carbonates (Midwood and Boutton 1998). Samples were then washed to neutrality with distilled water, dried at 55 °C until a constant weight was achieved, and stored for analysis of SOC content. SOC content was analyzed by combustion using an elemental analyzer (vario TOC cube, Elementar, Germany) monitored with standard samples of Low Organic Content Soil OAS (CatNo B2152) in Laboratory of Surficial Environment Geochemistry, China University of Geosciences (Beijing). The precision of SOC content determination was better than 2.0%.

2.2 Data processing and statistical analysis

The mean weight diameter (MWD) of soil aggregate (mm) was calculated as follows:

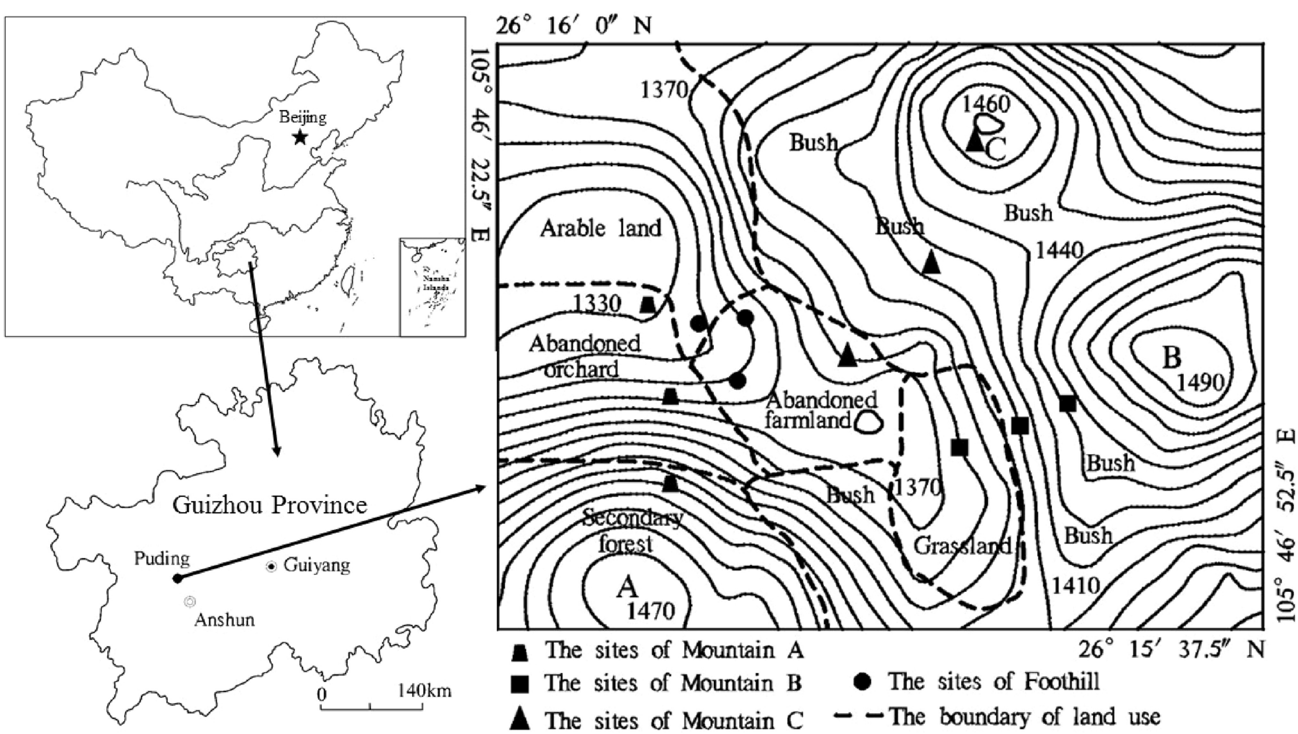

Fig. 1 Land use and sample site distribution

Table 1 Slope position, land use, SIC (soil inorganic carbon), SOC (soil organic carbon), aggregate composition, and MWD (mean weight diameter) of different sample sites

Slope position	Land use	Altitude (m)	SIC (g kg^{-1})	SOC (g kg^{-1})	Aggregate composition			MWD (mm)
					Ma-A (%)	Mi-A (%)	S–C (%)	
Mountain A								
Upper slope	SF	1442	0.83	75.96	77.98	5.88	10.93	0.94
Middle slope	AO[1]	1365	1.67	27.57	77.04	7.18	10.99	0.92
Lower slope	AO[2]	1320	4.94	37.39	77.78	7.23	10.71	0.93
Mountain B								
Upper slope	Bush	1425	5.23	47.27	82.31	6.73	6.88	0.98
Middle slope	Bush	1404	6.22	39.45	76.01	8.37	11.57	0.91
Lower slope	GL	1376	3.18	22.21	74.35	9.16	12.25	0.89
Mountain C								
Upper slope	Bush	1466	42.03	41.21	80.64	7.60	8.49	0.95
Middle slope	Bush	1401	6.27	37.46	75.77	8.62	12.35	0.90
Lower slope	AF[3]	1370	2.54	23.77	71.55	9.39	15.52	0.85
Foothill								
Lower slope	AL	1335	1.08	10.96	35.55	17.55	42.30	0.46
Lower slope	AF[4]	1335	3.00	23.63	67.30	12.39	16.62	0.81
Lower slope	AF[4]	1333	1.67	20.76	63.89	12.15	19.65	0.78

Note Ma-A macro-aggregate, *Mi-A* micro-aggregate, *S–C* silt and clay fraction, *SF* secondary forest, *AL* arable land, *GL* grassland

[1] Abandoned orchard evolved to secondary forest (5 years)

[2] Abandoned orchard evolved to bush (5 years)

[3] Abandoned farmland evolved to secondary forest (8 years)

[4] Abandoned farmland evolved to grassland (3 years)

$$\mathrm{MWD} = \sum\nolimits_{k=1}^{n} (X_k \times M_k) \quad (1)$$

where X_k (mm) is the mean diameter of each aggregate, M_k (%) is the mass proportion of aggregates in bulk soils, and k is the number of aggregates ($k = 1, 2, 3$).

The aggregate-associated SOC content in bulk soils, $C_k^{'}$ (g kg^{-1}), was calculated as follows:

$$C_k^{'} = C_k \times M_k \quad (2)$$

where C_k (g kg^{-1}) is the SOC content in different aggregate fractions and M_k is as above.

Statistical analyses were performed using the SPSS PASW Statistical v18.0 software package, and figures were drawn with the SigmaPlot 12.5 software package.

3 Results and discussion

3.1 Aggregate composition and SOC content

The mass proportion of macro-aggregates in bulk soils and MWD decreased from the upper to the lower slope (Table 2) and under different land use as follows: secondary forest > abandoned orchard > bush > grassland > abandoned farmland > arable land (Table 1). However, the proportion of micro-aggregates and silt and clay fractions displayed a different trend. With the exception of arable land, the proportion of macro-aggregates (>60%) was higher than that of micro-aggregates (<15%) and silt and clay fractions (<20%). The silt and clay fractions accounted for 42% of arable land soil, macro-aggregates for 35%, and micro-aggregates for 17% (Table 1).

The SOC content of bulk soils and different aggregates decreased from the upper to the lower slope (Table 3) and under different land uses as follows (Fig. 2): secondary forest > bush > abandoned orchard > abandoned farmland > grassland > arable land. Arable land was again the exception, with the highest SOC content in macro-aggregates, and the lowest in silt and clay fractions. For other land uses, the SOC content of aggregates decreased as follows: micro-aggregates > macro-aggregates > silt and clay fractions.

3.2 Effects of slope position on aggregate-associated SOC sequestration

The proportion of macro-aggregates and the MWD of soil aggregates decreased from the upper to the lower slope,

Table 2 The mass proportion of different aggregates in bulk soils and MWD (mean weight diameter) at different slope positions (mean ± SD)

Slope position	Macro-aggregate (%)	Micro-aggregate (%)	Silt and clay (%)	MWD (mm)
Upper slope	80.31 ± 2.19a	6.74 ± 0.86b	8.77 ± 2.04b	0.96 ± 0.02a
Middle slope	76.27 ± 0.68b	8.06 ± 0.77b	11.64 ± 0.01b	0.91 ± 0.01a
Lower slope	65.07 ± 15.28b	11.31 ± 3.62a	19.51 ± 11.61a	0.78 ± 0.17b

Note a, b indicate significant differences among the slope positions at $p < 0.05$ level based on the least significant difference (LSD) test

Table 3 The SOC content in bulk soils and aggregates at different slope positions (mean ± SD)

Slope position	Bulk soil ($g \cdot kg^{-1}$)	Macro-aggregate ($g \cdot kg^{-1}$)	Micro-aggregate ($g \cdot kg^{-1}$)	Silt and clay ($g \cdot kg^{-1}$)
Upper slope	54.81 ± 18.56a	56.52 ± 18.69a	64.92 ± 21.26a	45.67 ± 9.78a
Middle slope	34.83 ± 6.36a	33.85 ± 13.49b	42.98 ± 7.94a	30.56 ± 4.28b
Lower slope	23.12 ± 8.47b	24.54 ± 8.80b	27.33 ± 11.94b	19.65 ± 7.75b

Note a, b indicate significant differences among the slope positions at $p < 0.05$ level based on the least significant difference (LSD) test

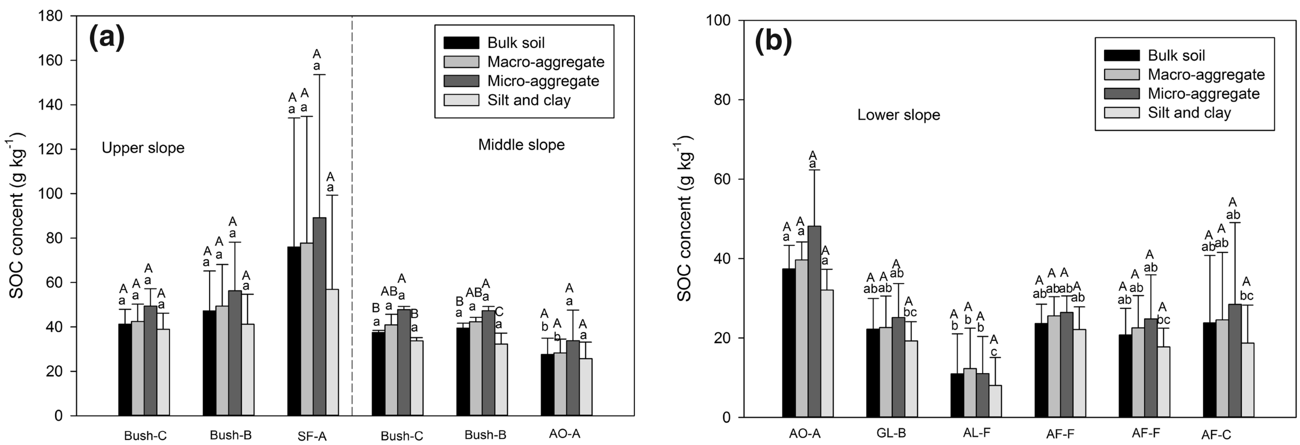

Fig. 2 The SOC contents in bulk soils and aggregates at different slope positions under different land uses. The details of land use types are shown in Table 1. On the x-axis, *SF* secondary forest, *AO* abandoned orchard, *GL* grassland, *AL* arable land, *AF* abandoned farmland; *A*, *B*, *C*, and *F* denote samples from Mountain A, Mountain B, Mountain C, and Foothill, respectively. *Error bars* are SD of means (average values of 0–10, 10–20, and 20–30 cm soil depth, n = 3). *Different capital letters above error bars* indicate significant differences among different aggregates, and *different lowercase letters* indicate significant differences between different land use types for the same aggregates of same slope positions at $p < 0.05$ based on the least significant difference (LSD) test

while the proportion of micro-aggregates and silt and clay fractions increased. The SOC content in bulk soils and all aggregate fractions decreased from the upper to the lower slope and the degree of soil erosion decreased with a decrease in slope steepness. Soil erosion preferentially transfers fine soil particles, decreases recalcitrant SOC at erosion sites, and increases the decomposition of SOC at deposition sites (Yu et al. 2006). Carbon-rich and labile plant residues are usually protected in macro-aggregates, while carbon-poor and stable SOC is occluded in micro-aggregates (Blanco-Canqui and Lal 2004). This indicates that soil structure and SOC storage are impacted by slope position, possibly due to soil erosion.

3.3 Effects of land use on aggregate-associated SOC sequestration

The SOC content of bulk soils generally increased with an increase in MWD and in proportion of macro-aggregates under different land uses. Land use affected both content and composition of SOC inputed to soil. SOC dynamics were associated with the formation and development of

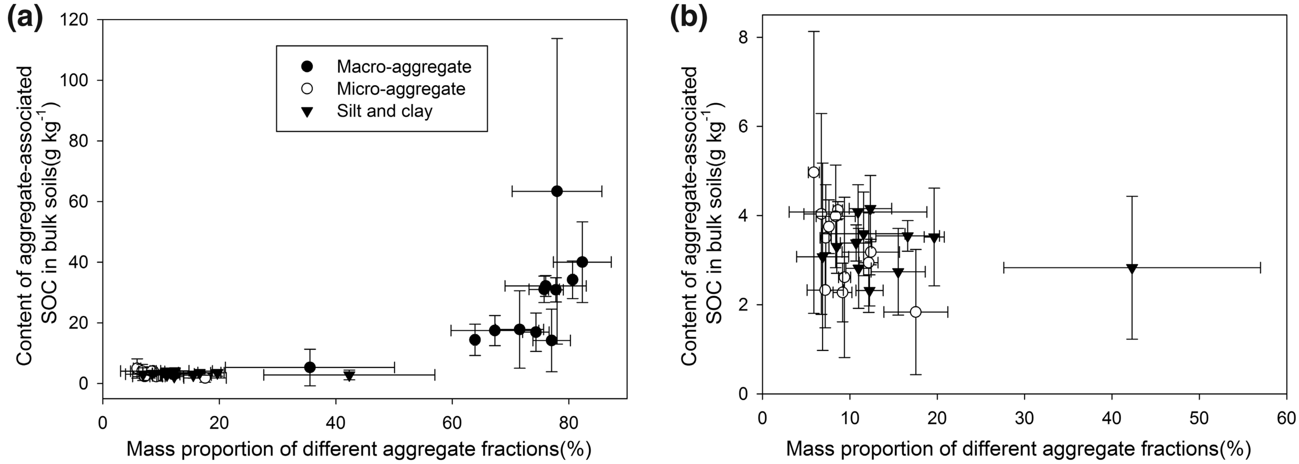

Fig. 3 Mass proportion of different aggregate fractions versus content of aggregate-associated SOC in bulk soils under different land uses. *Error bars* are SD of means (mean is an average from 0–10, 10–20, and 20–30 cm depth SOC content, n = 3). Plot **a** includes macro-aggregates, micro-aggregates, and silt and clay fractions. Plot **b** is a partially enlarged drawing of **a**, and includes micro-aggregates and silt and clay fractions only

aggregates. The soil under bush on the upper slope contained a higher proportion of macro-aggregates than soil under secondary forest, possibly because soil erosion preferentially transferred micro-aggregates and silt and clay fractions. Grassland soil had a lower SOC content than abandoned farmland, likely due to the influence of current vegetation cover. The high micro-aggregate associated SOC content in the vast majority of soils probably resulted from the accumulation of C-rich decomposed SOC. However, recalcitrant and C-poor SOC was combined with minerals in the silt and clay fractions, resulting in a low SOC content. Tillage strongly affects soil aggregate composition and the SOC content associated with aggregates (Six et al. 1998). Abandoned farmland soils had a higher SOC content and proportion of macro-aggregate fractions than arable land soils had, indicating that a decrease in human disturbance facilitates the accumulation of macro-aggregates and SOC. Therefore, converting farmland to forest or grassland may facilitate macro-aggregate formation, SOC storage, and soil structure improvement.

3.4 Contribution of aggregates to SOC sequestration

Micro-aggregates and silt and clay fractions were focused on a small region around their origin, indicating that macro-aggregates make a greater contribution than other aggregate fractions to both the mass of bulk soils and the SOC content (Fig. 3). There was a positive linear correlation between the proportion of macro-aggregates and the content of aggregate-associated SOC in bulk soils, indicating that macro-aggregate-associated SOC increases with the proportion of macro-aggregates. Our results suggest that the accumulation of macro-aggregates can facilitate SOC storage.

4 Conclusions

The proportion of macro-aggregates and MWD decreased from the upper to the lower slope, and decreased under different land uses as follows: secondary forest > abandoned orchard > bush > grassland > abandoned farmland > arable land. The SOC content of bulk soils and the different aggregates decreased from the upper to the lower slope, and decreased under different land uses as follows: secondary forest > bush > abandoned orchard > abandoned farmland > grassland > arable land. The SOC content generally increased with an increase in MWD and an increase in the proportion of macro-aggregates under the different land uses. The results of our study indicate that the accumulation of macro-aggregate can facilitate SOC storage.

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Compliance with ethical standards

Conflict of interest We declare no conflict of interest.

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